Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-50-TR–2003/029 Aug 2003

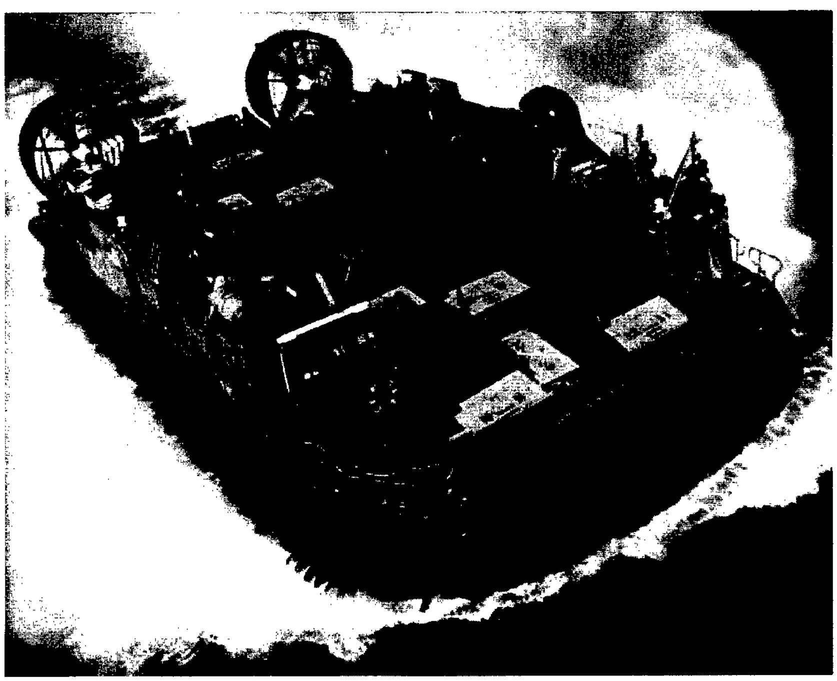
Hydromechanics Directorate

Technical Report

Propeller Inflow Measurements on an Air Cushion Landing Craft Vehicle (LCAC)

by

Scott Gowing



NSWCCD-50-TR–2003/029 Propeller Inflow Measurements on an Air Cushion Landing Craft Vehicle (LCAC)

MAJOR CARDEROCK DIVISION TECHNICAL COMPONENTS

CODE	011	Director of Technology
	10	Machinery Systems/Programs and Logistics Directorate
	20	Ship Systems and Programs Directorate
	50	Hydromechanics Directorate
	60	Survivability, Structures and Materials Directorate
	70	Signatures Directorate
	80	Machinery Research and Development Directorate
	90	Machinery In-Service Engineering Directorate

CARDEROCK DIVISION, NSWC, ISSUES THREE TYPES OF REPORTS:

1. **CARDEROCKDIV reports, a formal series,** contain information of permanent technical value. They carry a consecutive numerical identification regardless of their classification or the originating directorate.

2. **Directorate reports, a semiformal series,** contain information of a preliminary, temporary, or proprietary nature or of limited interest or significance. They carry and alphanumerical identification issued by the originating directorate.

3. **Technical memoranda, an informal series,** contain technical documentation of limited use and interest. They are primarily working papers intended for internal use. They carry an identifying number which indicates their type and the numerical code of the originating directorate. Any distribution outside CARDEROCKDIV must be approved by the head of the originating directorate on a case-by-case basis.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY ***(Leave Blank)***

2. REPORT DATE
aUG 2003

3. REPORT TYPE AND DATES COVERED
Final, aUG 2003

4. TITLE AND SUBTITLE
Propeller Inflow Measurements on an Air Cushion Landing Craft Vehicle (LCAC)

5. FUNDING NUMBERS
Ref No. N0001403WX20493
Doc No. N6133103WR00106
Work Unit 03-1-5400-820

6. AUTHOR(S)
Scott Gowing

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Propulsion and Fluid Systems Department, Code 5400
NSWC, Carderock Division
9500 MacArthur Blvd.
West Bethesda, MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-50-TR-2003/029

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commanding Officer
Coastal Systems Station, Dahlgren Div, NSWC
6703 West Highway 98
Panama City, FL 32407-7001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12.a DISTRIBUTION / AVAILIBILITY STATEMENT
Distribution is unlimited

12.b DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Air inflow velocity data are presented for the starboard propulsion propeller of an LCAC vehicle. Data at various radial and angular locations centered on the propeller shaft are shown for two stations upstream of the propeller but behind the LCAC superstructure. Test conditions include multiple speeds over water as well as bollard conditions at full power. Severe velocity deficits are found in the lower outboard quadrant of the inflow, and these deficits become more severe closer to the back face of the craft superstructure.

16. SUBJECT TERMS
LCAC air cushion wake velocity survey

15. NUMBER OF PAGES
26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

(THIS PAGE INTENTIONALLY LEFT BLANK)

CONTENTS

TABLES

FIGURES

(THIS PAGE INTENTIONALLY LEFT BLANK)

ABSTRACT

Air inflow velocity data are presented for the starboard propulsion propeller of an LCAC vehicle. Data at various radial and angular locations centered on the propeller shaft are shown for two stations upstream of the propeller but behind the LCAC superstructure. Test conditions include multiple speeds over water as well as bollard conditions at full power. Severe velocity deficits are found in the lower outboard quadrant of the inflow, and these deficits become more severe closer to the back face of the craft superstructure.

ADMINISTRATIVE INFORMATION

This work was sponsored by the Naval Coastal Systems Station, Dahlgren Div, NSWC for an Office of Naval Research (ONR) Program, Element 0603236N, Task 02915. The work was conducted by the Propulsion and Fluid Systems Department (Code 5400) of the Hydromechanics Directorate of the Naval Surface Warfare Center, Carderock Division (NSWCCD), under work unit number 03-1-5400-820 in March and April of 2003.

INTRODUCTION

Propeller propulsion for naval vehicles involves simultaneously satisfying requirements for powering, engine characteristics, acoustics and vibration, space constraints, etc. that often conflict with each other for optimization. In the case of the design of the LCAC propulsion propeller, space constraints and power plant arrangements force the propeller to be located behind the craft's superstructure. The superstructure wake creates asymmetry in the propeller inflow, leading to unsteady blade forces that create noise and vibration as well as efficiency losses in the form of shed vorticity. Although these asymmetries in the flow cannot be eliminated within the existing design constraints, the design of a subsequent propeller can be improved by adapting the design (blade section, rake, skew, pitch, material, etc) to the inflow as it exists. Towards this end, computer codes can predict the propeller inflow to some accuracy and be used as design guidance, but these codes can be sensitive to various phenomena that are difficult to fully replicate in a complicated flow field such as a superstructure wake. Physical air velocity measurements can serve to either calibrate or verify a numerical prediction, or be used by themselves for mapping the propeller inflow and serving as input to the propeller design.

Towards this end, NSWCCD Code 5400 was tasked with measuring the inflow to the starboard propeller on an LCAC vehicle over a range of speeds, including bollards, in two planes between the propeller and superstructure. The port propeller inflow was not measured because of time and funding constraints. Because the superstructure on an LCAC is symmetric on the port and starboard sides towards the rear of the craft, the air flow pattern into the port propeller is assumed to be a mirror image of the starboard flow pattern.

TEST CONDITIONS

Measurements were made at 25, 35, and 45 knots going both upwind and downwind on a ESE-WNW track in St. Andrews bay, adjacent to Panama City, FL. The test was done on LCAC hull number 66 carrying an M60 tank as payload in the center of the craft. Figure 1 shows an overview of the craft and Figure 2 shows the tank. Table 1 summarizes the vehicle and environmental conditions, including weather data from the hourly records of Tyndall Air Force Base located adjacent to St. Andrews Bay.

Because the lift fan engines and propeller engines have to run at the same RPM, the only method of varying thrust is adjusting the propeller pitch, with the maximum propeller pitch being 42 degrees. The propeller pitch data including their statistics are also shown in Table 1. Beyond instrument noise, the standard deviation of the pitch data may be an indicator of the pitch changes used to maintain constant speed under varying wind gust loads on the vehicle. In turn, this would indicate the unsteadiness of the wind itself.

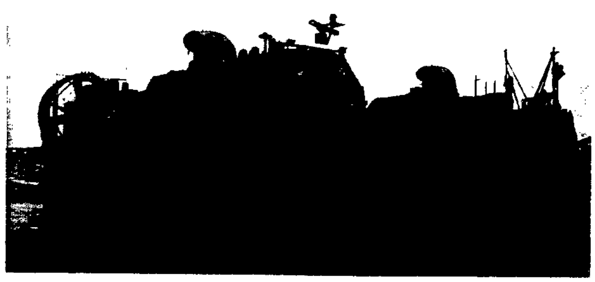


Figure 1 LCAC test vehicle

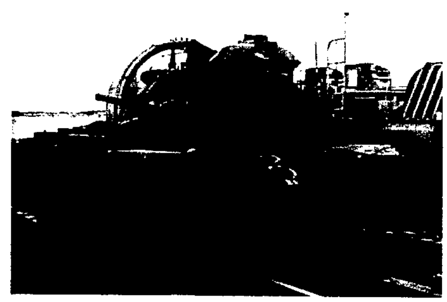


Figure 2 M60 tank payload

Table 1 LCAC vehicle and wind conditions

		rake	rake	heading (degs)				speed (kts)				wind data direction	wind data mean speed	gust[1] speed	propeller pitch (degs)			
run	Vship	orientation	position	mean	std dev	min	max	mean	std dev	max	min	(degs)	(kts)	(kts)	mean	std dev	max	min
3	full power	diag.	midway									300	10		40.2	0.1	40	40
4	25 kts	diag.	midway	109	4	100	118	26.7	1.0	25	29	300	10		17.7	1.8	14	21
5	35 kts	diag.	midway	121	4	113	130	36.1	0.9	34	38	300	10		19.5	2.2	15	24
6	25 kts	diag.	midway	304	6	292	317	27.5	1.0	26	29	300	12		25.4	2.7	20	31
7	35 kts	diag.	midway	292	3	287	298	37.6	1.0	36	40	300	12		28.1	1.7	25	31
8	45 kts	diag.	midway	119	6	108	131	45.3	1.1	43	48	300	12		26.2	1.2	24	29
9	45 kts	diag.	midway	298	6	286	311	48.2	1.2	46	51	300	12		31.3	1.8	28	35
11	full power	ortho.	midway									290	13		40.0	0.0	40	40
13	25 kts	ortho.	midway	111	6	100	122	26.6	1.0	25	29	320	16		17.8	1.8	14	21
14	25 kts	ortho.	midway	299	4	292	307	27.3	0.8	26	29	320	16		26.2	1.8	23	30
15	35 kts	ortho.	midway	114	5	103	124	36.6	0.8	35	38	320	16		19.4	1.4	17	22
16	35 kts	ortho.	midway	297	1	295	299	37.9	0.7	37	39	320	16		26.6	0.8	25	28
17	45 kts	ortho.	midway	115	5	106	124	45.1	1.2	43	47	320	16		26.3	2.1	22	30
18	45 kts	ortho.	midway	301	7	288	315	48.2	1.1	46	50	320	16		31.3	2.6	26	37
21	full power	ortho.	downstrm									300	14		40.1	0.0	40	40
22	25 kts	ortho.	downstrm	109	8	94	124	26.7	1.2	24	29	300	14		17.7	3.6	11	25
23	35 kts	ortho.	downstrm	123	8	108	138	35.8	1.2	33	38	300	14		29.3	3.6	22	36
24	25 kts	ortho.	downstrm	305	4	296	313	26.8	1.1	25	29	300	11	18	37.4	1.5	34	40
25	35 kts	ortho.	downstrm	297	2	293	301	37.4	1.4	35	40	300	11	18	36.2	6.2	24	49
26	45 kts	ortho.	downstrm	116	8	101	131	46.2	1.2	44	49	300	11	18	38.3	2.0	34	42
27	45 kts	ortho.	downstrm	298	3	291	304	48.1	1.3	46	51	300	11	18	30.7	2.7	25	36
30	full power	diag.	downstrm									290	10		no data	no data	no data	no data
31	25 kts	diag.	downstrm	108	5	99	117	26.1	1.7	23	30	290	10		20.2	5.8	9	32
32	35 kts	diag.	downstrm	122	7	107	137	35.4	0.7	34	37	290	10		22.7	3.0	17	29
33	25 kts	diag.	downstrm	304	5	295	313	26.8	2.4	22	32	290	10		36.0	5.6	25	47
34	35 kts	diag.	downstrm	298	7	285	312	37.8	1.7	34	41	290	10		40.2	5.2	30	51
35	45 kts	diag.	downstrm	123	6	110	135	44.6	1.6	41	48	290	10		28.6	7.2	14	43
36	45 kts	diag.	downstrm	301	6	289	312	47.7	1.0	46	50	290	10		28.6	5.3	18	39

1) Gusts are noted if maximum wind speed exceeds minimum wind speed by 5 knots or more.

EXPERIMENTAL EQUIPMENT

KIEL PROBE RAKE ASSEMBLY

The Kiel probe rake assembly was composed of 2 in. aluminum pipe pieces fastened to a collar that clamped around the propeller drive shaft housing. The collar design allowed the pipe pieces to be assembled perpendicular to each other in the vertical and horizontal planes ("orthogonal orientation"), or at a 45-degree angle to that position ("diagonal orientation"). The rake was positioned at two stream-wise positions, 7 ft 6 in. forward ("midway position") and 4 ft 4 in. forward ("downstream position") of the propeller, respectively. The pipe ends were attached to the vehicle superstructure with cables or bolts for support. Figure 3 shows the arrangement, and Figure 4 shows a Kiel probe. Each Kiel probe was pneumatically connected with 1/16 in. plastic tubing to the Scanivalve module, and all tubes were made the same length to make the response time of each probe equal. The probes were frequently purged with high-pressure nitrogen to insure that they did not clog with water spray. Although the tubing was only 1/16 in. on the inside and the Kiel probe taps were 0.047 in. internal diameter, the body of the Kiel probe was ¼ in. diameter, and this allowed a small amount of water to collect inside the Kiel probe without blocking the pneumatic connection. Five probes were used on each rake arm at radii of 0.25, 0.50, 0.66, 0.79, and 0.90 of the shroud inlet radius (6.50 ft). The propeller diameter is slightly smaller with a diameter of 11.0 ft.

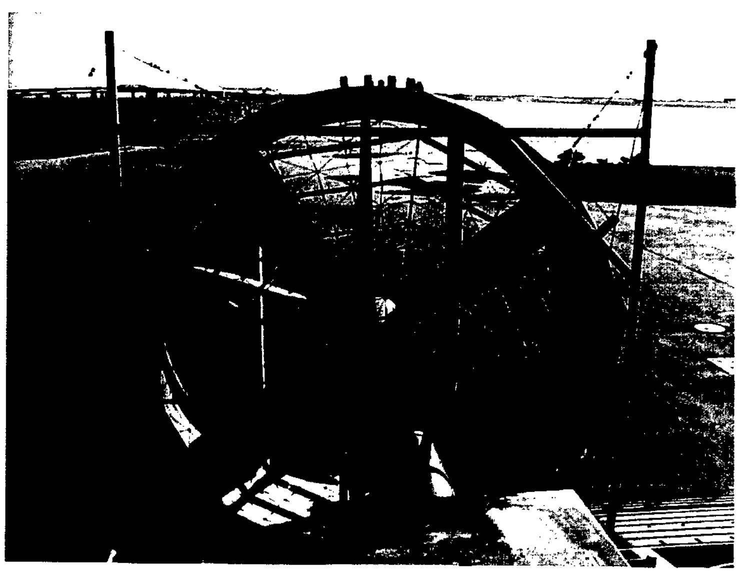


Figure 3 Kiel probe rake assembly (diagonal orientation)

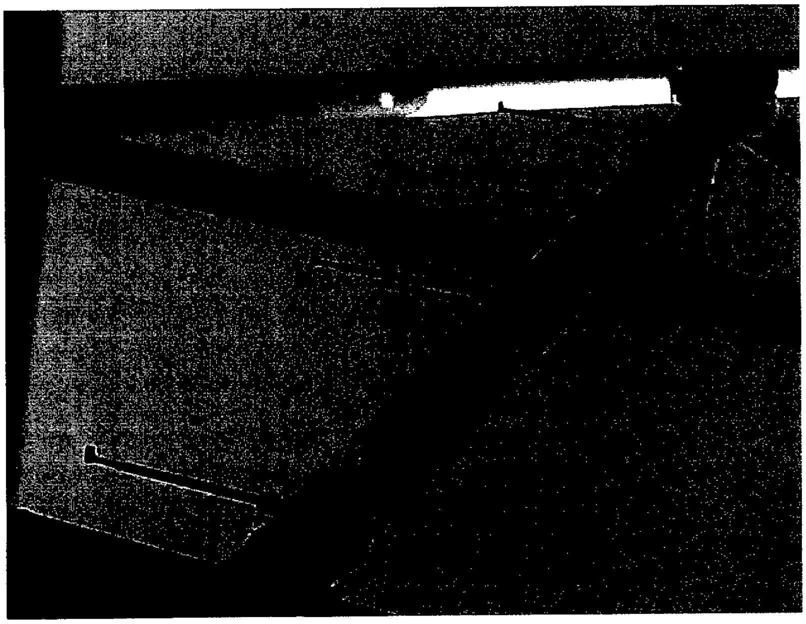


Figure 4 Kiel probes on rake

INSTRUMENTATION

The Kiel probes were connected via tubing to a differential pressure transducer, and the reference side of the transducer was connected to a static pressure tube placed in the center of the rake assembly. The resulting differential measurement represented the dynamic pressure of the air stream, and the velocity was derived from that value using air densities calculated from measured pressure, temperature, and relative humidity. The Kiel probe measures total pressure up to yaw or pitch angles of 45 degrees with no need for correction. The pressure from each Kiel probe was sequentially connected ("scanned") to the transducer using a Scanivalve Pressure Scanning Module with 48 pressure ports. The strain-gaged differential transducer fit inside the Scanivalve module and had a pressure range of 18 in. of water.

To account for wind variations and craft speed, a transducer was also connected to an independent Kiel probe rigged on top of the mast stantion atop the port cabin. Its data were collected as part of the Scanivalve port scanning process.

A 10 torr Barocel differential pressure standard was used to calibrate the transducers through the Scanivalve system. Each scan of the Scanivalve measured the reference pressure relative to itself for a shunted zero value, as well as the pressure from the Barocel standard. This provided a check of the transducer zero-drift and gain errors.

All data were collected at 100Hz for 5 seconds using a laptop computer with LabView software, and the pressures were allowed to stabilize for two seconds after switching ports.

Previous laboratory measurements showed that the system had a 99% response time of 10 seconds for step pressure changes at the ends of the 1/16 in. tubes. This is the time required for the pressure in a Kiel probe/tube assembly to equalize after a step change in pressure on the face of the Kiel probe itself. But the response time for pressure stabilization within the Scanivalve transducer, while scanning from one pressure-stabilized tube to the next, was in the order of only tenths of a second. This is a result of the low volume used in the Scanivalve transducer and module. Figure 5 shows the instrument system.

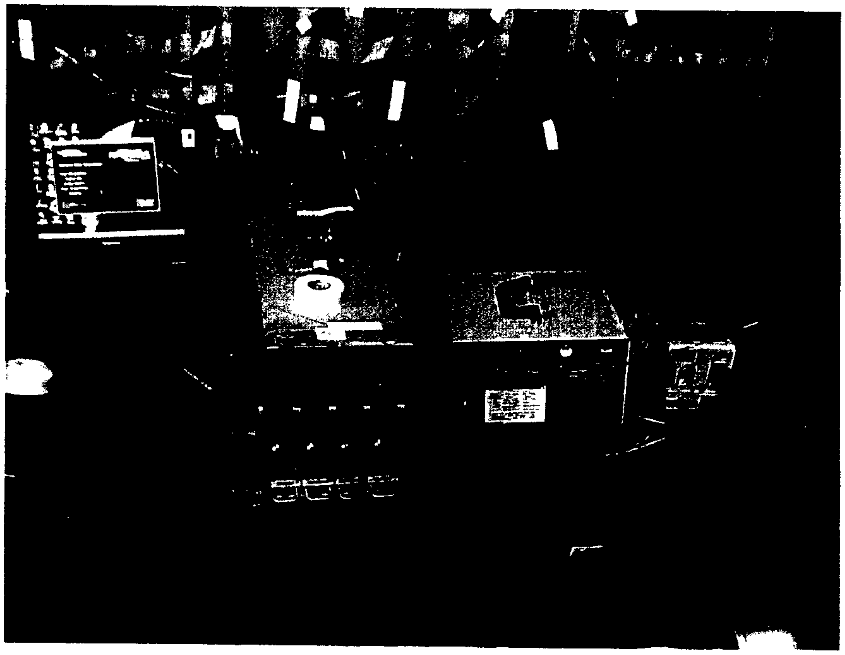


Figure 5 Instrument system

TEST SEQUENCE

Once the rake assembly was positioned, the probes were flushed with compressed nitrogen to make sure that no water clogged the lines, and readings were taken. These "zeros" were examined to look for high values that would indicate a problem (water clogged or pinched lines). The data were not always at zero because of wind passing over the probes, causing small readings, but clogged lines typically showed a large zero offset. The 'zeros' indicated wind speeds of 0-8 knots or so, but blocked or clogged lines showed differential pressures equivalent to 20 knots or more.

The vehicle was then brought to full power and bollard conditions were run without lifting off the parking pad. (The actual engine RPM varied slightly from day-to-day, within a few

percent, depending on ambient air conditions). After the bollards run, the vehicle lifted off and headed ESE (downwind) down St. Andrews Bay. Typically data were collected at 25 knots and 35 knots before turning around and heading in the reverse direction and repeating the data set over the same track. A separate run was made for the 45 knot test, again in both directions. The resulting vehicle tracks were within about 10 degs of the wind vector for the two downstream rake positions and the midway diagonal rake position. For the midway orthogonal rake position, the wind was about 27 degs off the port quarter going downwind, and 21 degs off the starboard bow going upwind. During each test run, the pilot tried to maintain constant GPS over-the-ground speed regardless of wind gusts, as opposed to maintaining constant propeller pitch or thrust. Although the bow thrusters (port and starboard) can pivot to help steer the craft, they were kept in the straight-ahead position to avoid blowing or sweeping air across the propeller inflow and contaminating the data. These thrusters are both yawed outboard at 18 degrees in the zero or straight-ahead setting, hence their exhaust may not impact the propeller inflow in the absence of cross winds.

After completing a set of runs with the rake in one position, the vehicle returned to base to move the rake and its support frame.

DATA REDUCTION

The differential pressures measured for each Kiel probe were converted to velocity values using air density calculated from the vehicle barometer and engine inlet temperature gage, and corrected for water vapor density determined from the morning weather report and a psychometric chart. (The moisture content of the air was assumed to be constant throughout the day).

REFERENCE PROBE

The differential pressure from the reference Kiel probe atop the port cabin stantion was corrected to be relative to the port cabin air pressure (instead of the static pressure ahead of the propeller), and the wind velocity was calculated assuming the static pressure at the reference probe equaled the port cabin pressure. This is a reasonable assumption because the port cabin had a vent open to the cargo deck area.

Originally the reference probe data was intended to provide a normalization for the Kiel probe data in one of two ways. The difference of the measured wind velocity relative to the vehicle speed could be linearly subtracted or added to the Kiel probe velocities, or the reference probe velocity itself could simply be used as the reference speed. Examination of the reference

probe data showed a difficulty, however. The average of the reference probe velocity data combined for the upwind and downwind tracks, at a given speed, was consistently 53% higher than the corresponding average of the vehicle speeds, instead of being equal to it. This phenomenon can physically be explained if the reference probe had been located in an area of accelerated flow over the vehicle bow, and this is likely what occurred. By reducing the reference probe velocities by this average ratio, the resulting average reference probe velocities and vehicle velocities were within a few percent of each other among the four tests run with the different rake positions and the three speeds. Figure 6 shows the correlation of the reference probe and craft speeds using this scaling ratio (1.53) for the different tests. During the testing, there was no higher location on the vehicle that could be used to reposition the reference probe and try to get out of the accelerated flow.

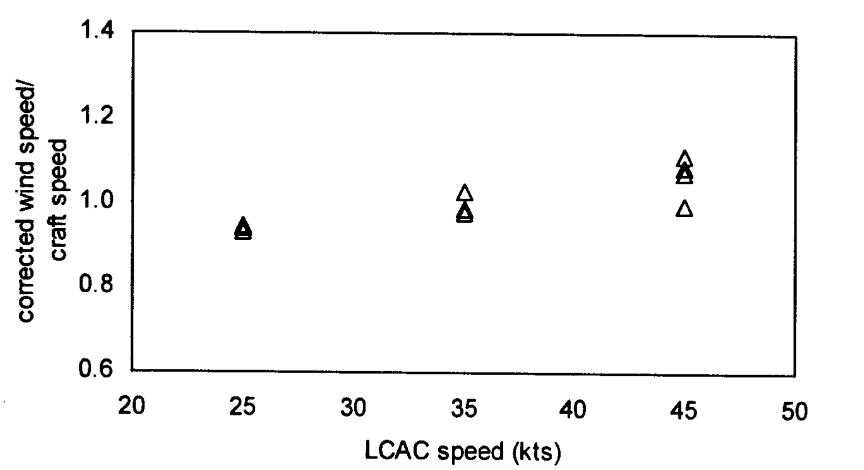


Figure 6 Ratio of corrected average reference probe to LCAC speeds

Even with the corrected reference probe data, normalizing the inlet flow Kiel probe data was not done because of other difficulties that would be introduced. For example, some of the probes were clearly located where the air flow was blocked by the superstructure, and adjusting their values based on wind speed changes in the freestream did not make sense. Making wind speed corrections to probes that were in the freestream would require interpretation of which probes were blocked or not, further confusing the issue. Drag variations on the vehicle caused by wind gusts would cause propeller pitch variations as the pilot tried to maintain constant speed, and these propeller pitch changes would influence the inflow as well.

The only further data reduction was to simply average the probe data for the corresponding upwind and downwind runs. To illustrate the difference in the data for unblocked versus blocked portions of the flow, Figure 7 compares upwind and downwind data for the top unblocked flow quadrant (12:00) and the lower, blocked quadrant (7:30).

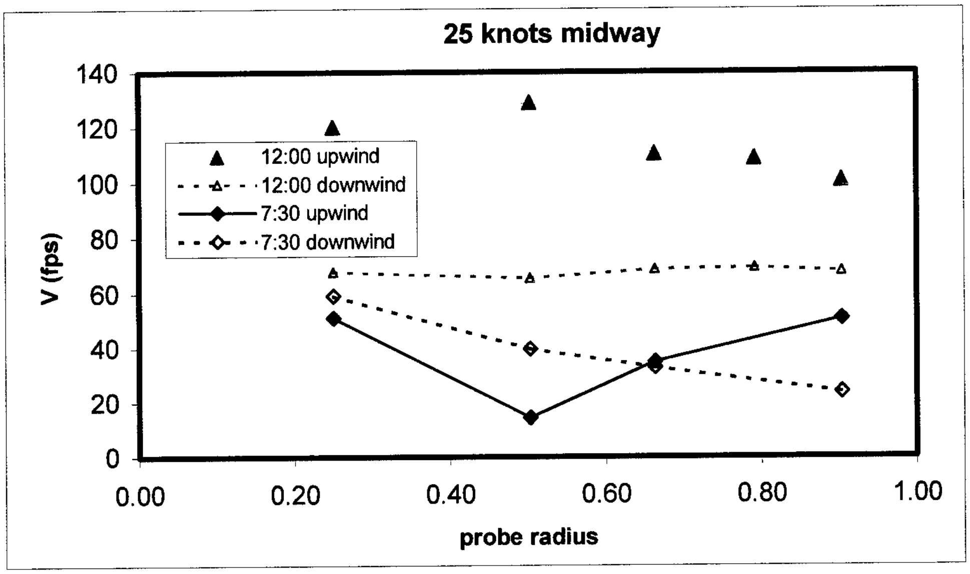


Figure 7 Comparison of upwind and downwind data

DATA ADJUSTMENT

Water spray clogged the static pressure line on runs 22-27, but the average value of the static pressures for the other runs at the same speeds and directions were used to correct those data. And some of the probes during other tests were either clogged or had negative differential pressure readings, and those values were ignored.

DATA ACCURACY

The overall instrumentation accuracy for measuring velocity is in the order of 1% to 2%, but a greater source of error is the assumption that the static pressure in the plane of the probes is constant [1]. All the Kiel probe data are derived assuming that the static pressure against which their differential pressure is measured is the same as the static pressure at the probe location. Yet the static pressure was measured only at the center of the rake assembly, in a sheltered location. Any curvature of the inflow towards the propeller implies a radial pressure gradient required to accelerate the flow in that direction, and certainly there will be curvature of the flow around the superstructure into the propeller. A Prandtl type pitot-static probe avoids this difficulty, but

requires alignment with the flow, which is unknown in this case. The Kiel probe enjoys the advantage of being misaligned to the flow yet still capturing the total pressure correctly. The error of the uniform static pressure assumption can be estimated by computation of the inlet flowfield, and examining the deviation of the static pressures (derived form potential flow) from the measured centerline value.

RESULTS

Figure 8 through Figure 11 show the resulting average velocities at the different radial and angular locations for bollards, 25 kts, 35 kts, and 45 kts, respectively. The angular locations are denoted by the position on a clock, looking downstream at the propeller, with 12:00 hrs being up and 6:00 being down. The rake positions are noted at the tops of the graphs.

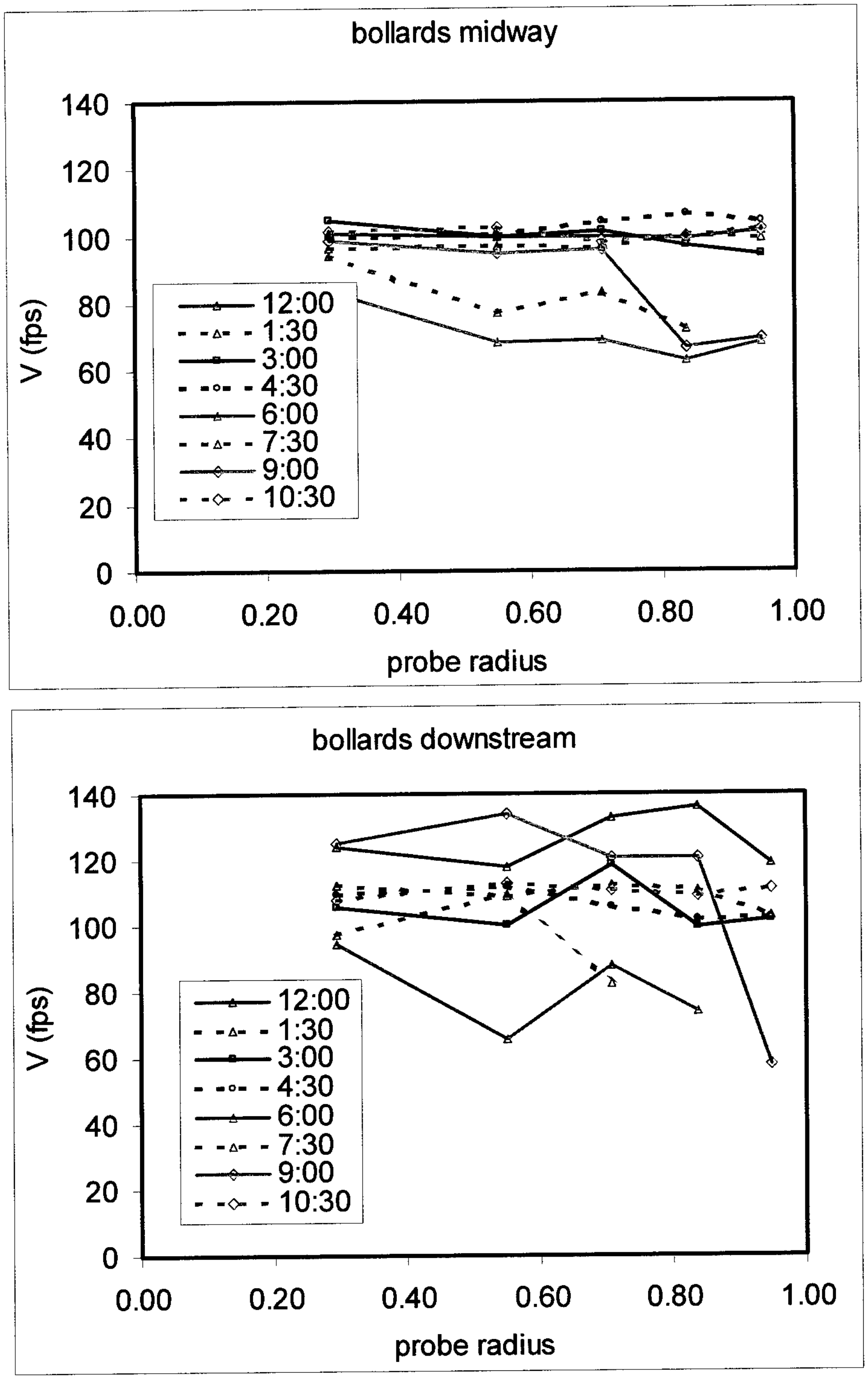
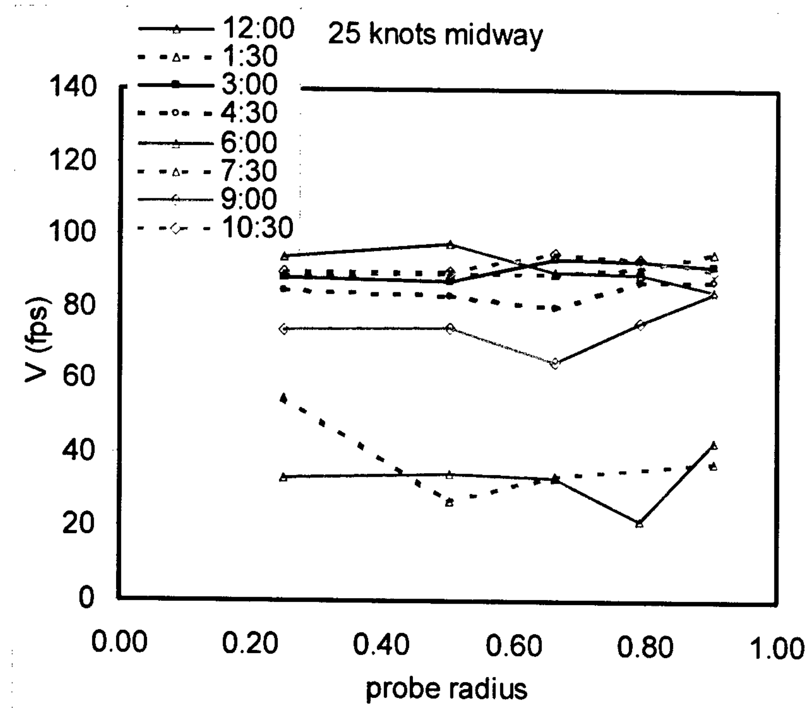


Figure 8 Bollard velocities



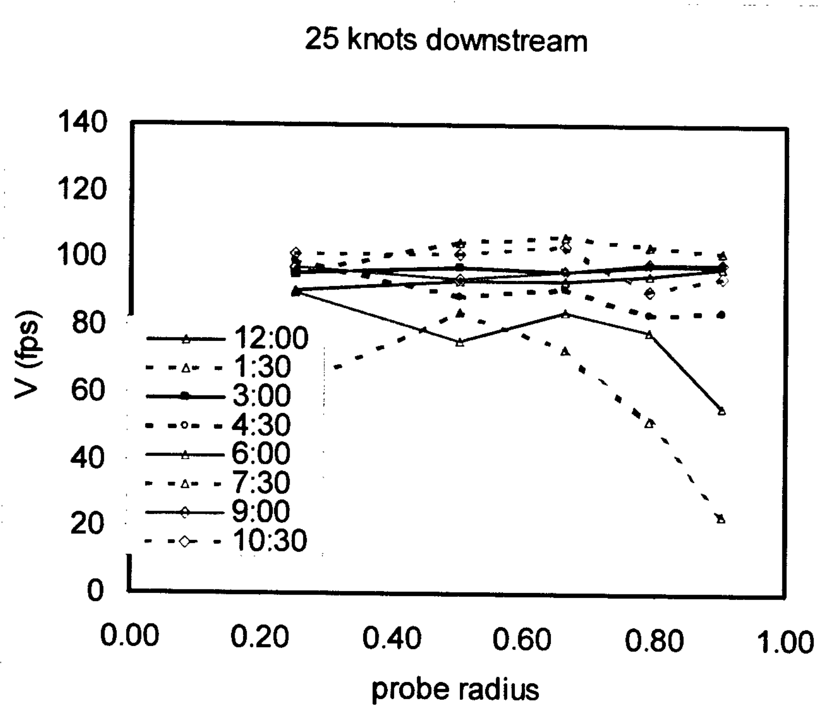


Figure 9 25 knot velocities

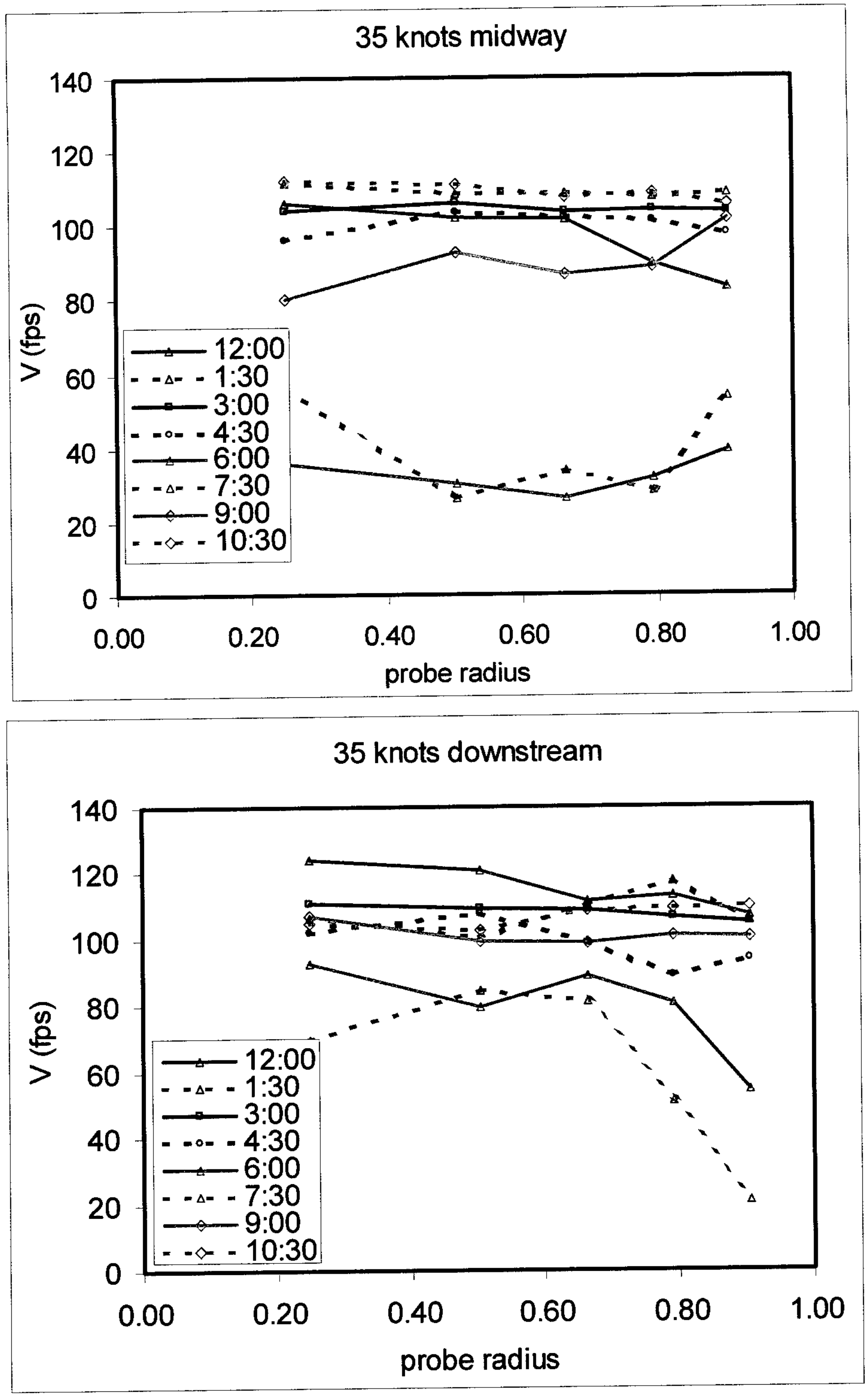
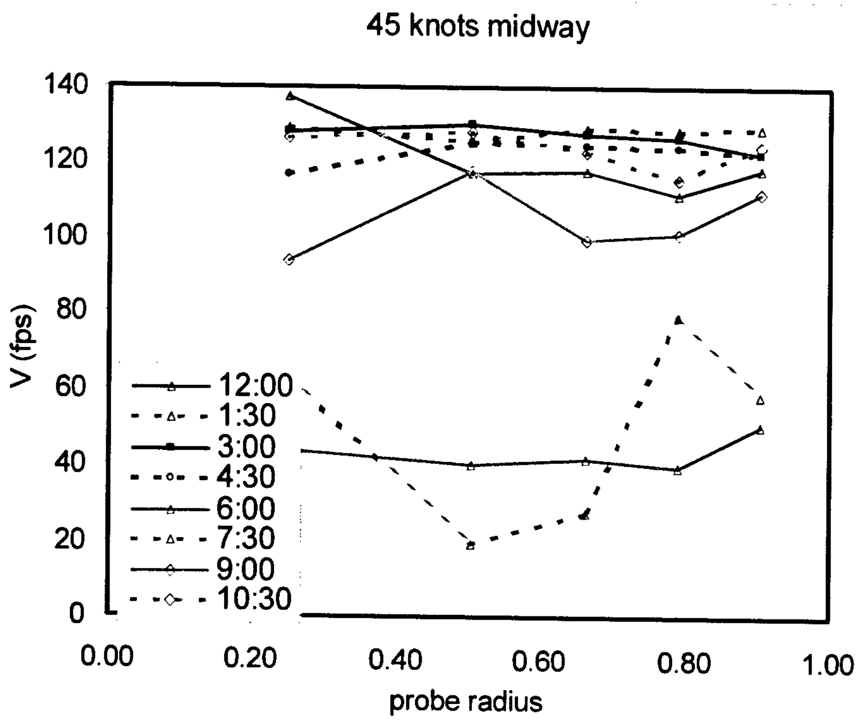


Figure 10 35 knot velocities



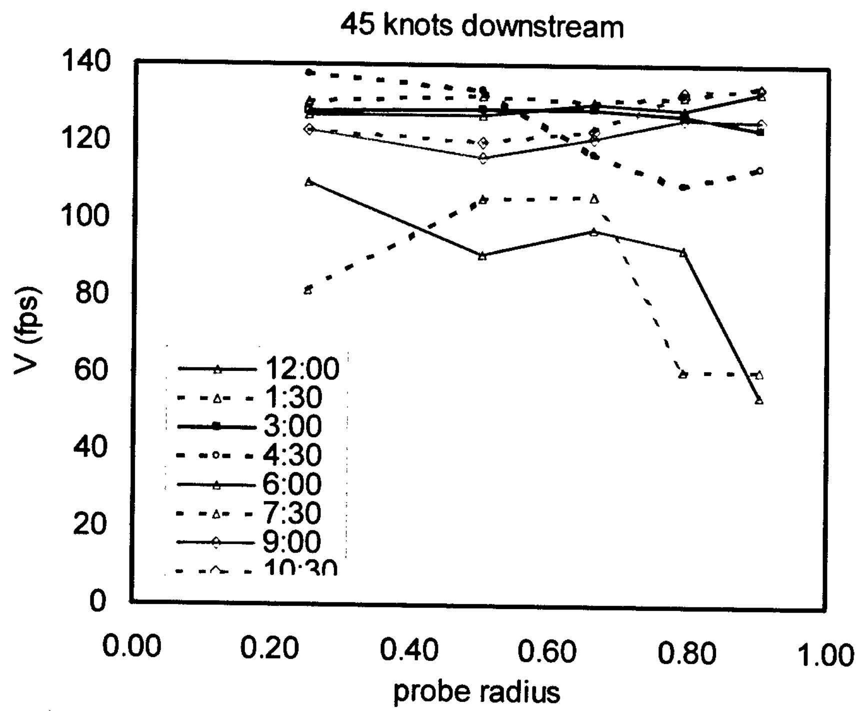


Figure 11 45 knot velocities

Overall the velocity graphs show deficits in the lower, outboard sectors of the inflow. These deficits are not surprising given the blockage of the propeller by the superstructure and the side panel that shields the propeller from waves along the side. The bollard data show velocity deficits at the 6:00 and 7:30 positions, and at the outboard positions at 9:00. The velocity uniformity improves moving downstream, but the deficit at the 9:00 outboard position remains for some reason. The 25 knot data show deficits again at 6:00, 7:30, and some at 9:00, and the velocities accelerate closer to the propeller. The low values at the tips of the 6:00 and 7:30 data in the downstream position may be caused by a short fence or skirt that runs along the bottom rail of the handrail upstream of the propeller, blocking the flow. This fence extends up 8 inches from the deck. The 35 knot and 45 knot data show similar patterns. Figure 12 shows the superstructure around the starboard propeller area to give an idea of the flow blockage.

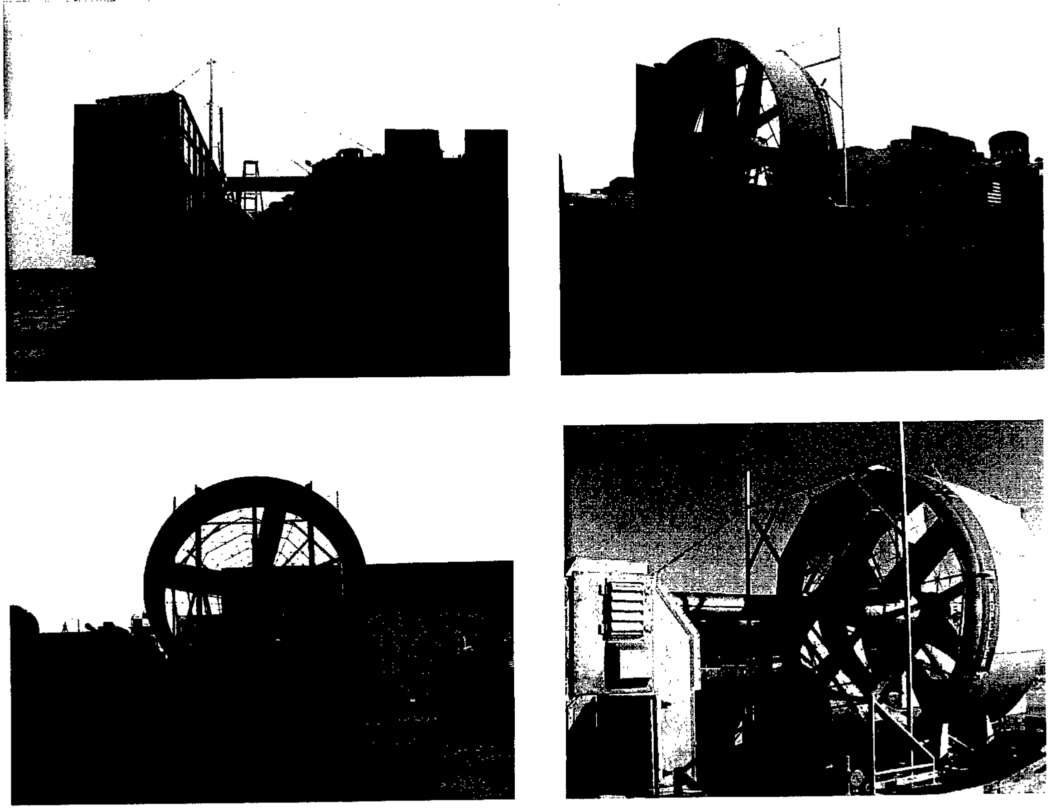


Figure 12 Views of starboard propeller

CONCLUSIONS

Air inflow velocities have been measured on a full-scale LCAC vehicle over a range of speeds, including bollards at full power. The measurements at two stream-wise locations and

eight angular positions show consistent velocity deficits in the region extending from the lower vertical angle to the horizontal outboard angle ahead of the propeller. Velocity deficits also appear near the outboard edge of the horizontal plane. Moving downstream towards the propeller, the velocities accelerate and become more uniform as well.

ACKNOWLEDGEMENTS

Many thanks go to Jeff Bohn from Computer Sciences Corporation and Vijay Kohli and David Lewis of the Fulcrum Corporation for helping to install the equipment and interpret the data. Thanks also go to Nam Trinh and the LCAC crew at NCSC (Dahlgren Div, NSWC) for helping to make this experimental program a success in a short time.

REFERENCES

1. Gowing, S., "Pressure and Shear Stress Measurement Uncertainty for DARPA SUBOFF Experiment," DTRC Report DTRC/SHD-1298-06 (January 1990).

(THIS PAGE INTENTIONALLY LEFT BLANK)

INITIAL DISTRIBUTION

EXTERNAL DISTRIBUTION

ORG.	NAME (Copies)
NAVSEA	
377J	B. Farnsworth
NCSS	
R51	N. Trinh
	D. Vickers
ONR	
36	L. Torres
334	G. Main
OPNAV	
N753L	W. Beverly
NASA	
MS 77-6	C. Miller
MS 77-6	B. Fite
NASACTC	G. Wright
Fulcrum Corp	
	V. Kohli
	D. Lewis
Computer Sciences Corp	
	J. Bohn
Band Lavis Assoc	
	A. Becnel
Hamilton Sundstrand	
	J. Neffinger
Dowty Propellers	
	M. Towkan
	R. Morgan
Goodrich Corp	
EPP	B. Smith
DTIC	(2)

CENTER DISTRIBUTION

CODE	NAME (Copies)
3421	NSWCCD Library
50	Koh
506	Walden
5200	Office Files
5300	Walker
5300	Office Files
5400	Gowing (8)
5500	Office Files